Advancing Lunar & Solar System Science & Exploration Through a Lunar Sample Return Campaign

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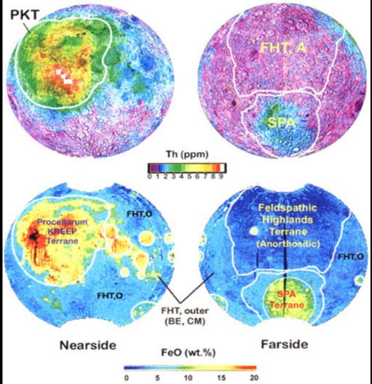
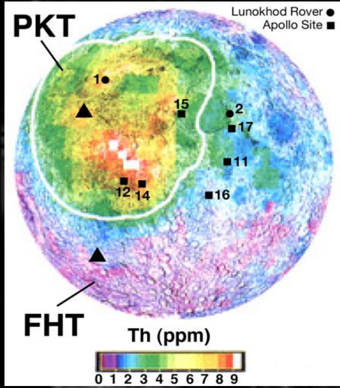
We need more samples than Apollo, Luna, & Lunar Meteorites

Subsequent missions have shown that the sample return sites were not ideal for exploring the Moon.





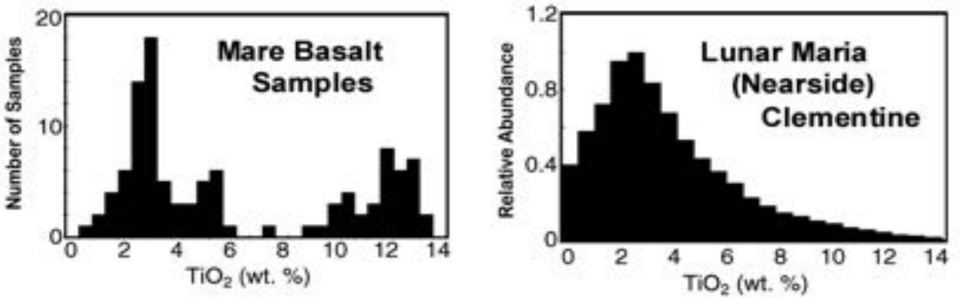
Lunar Terranes

- Apollo sites close to terrane boundaries.
- Samples contain PKT signature.

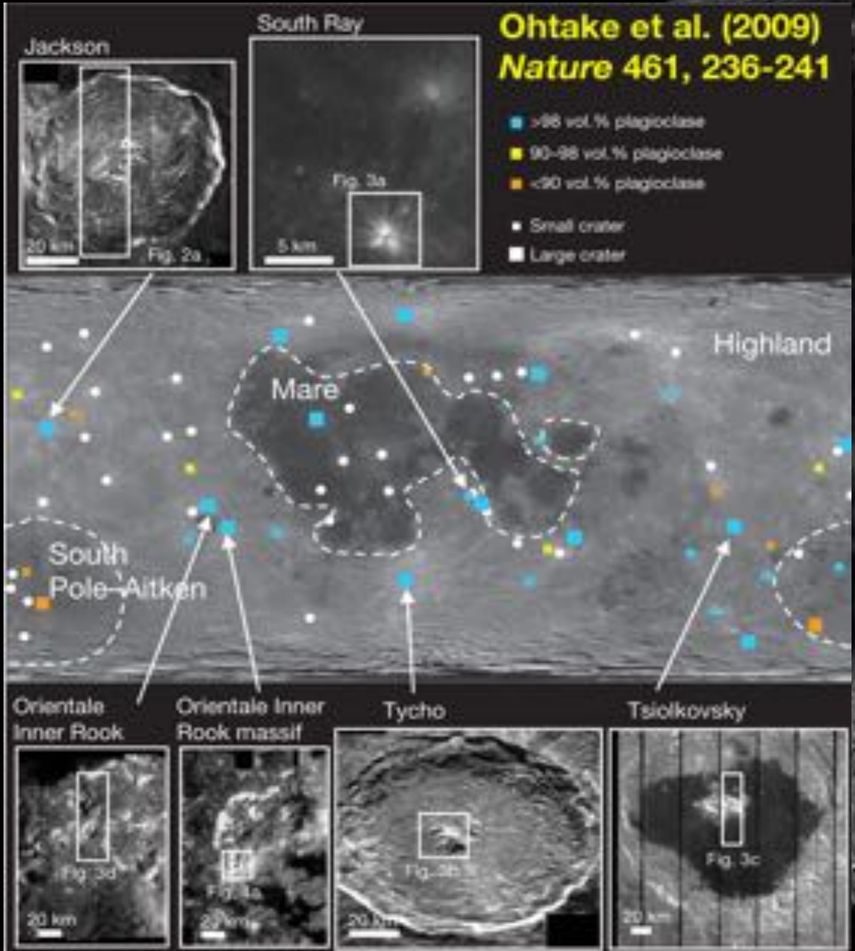
Jolliff et al. (2000) *JGR* **105**, 4197

- Apollo sample collection is not representative of the lunar compositional diversity.

Giguere et al. (2000) *MaPS* **35**, 193

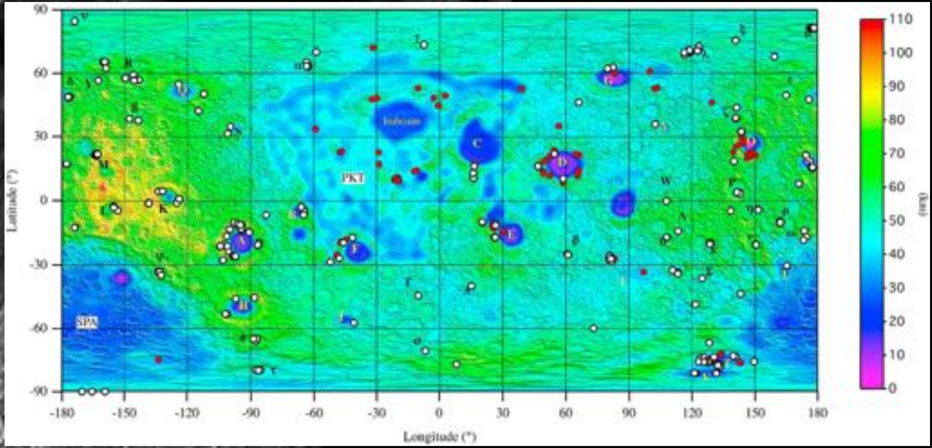


New Lunar Lithologies



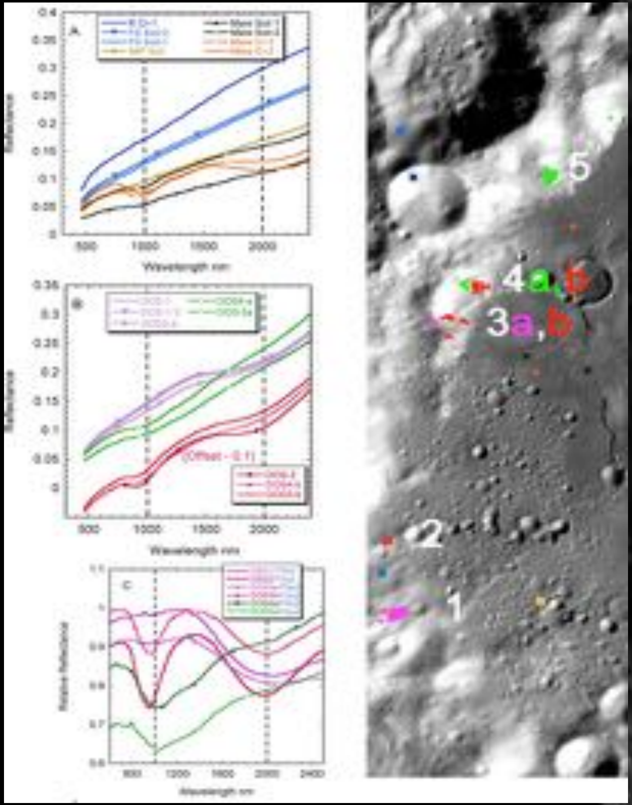
How do these new Rock Types (not represented in the sample collection) revise models of lunar evolution?

Pure Anorthosite or PAN: Kaguya



Yamamoto et al. (2012) *GRL* **39**, L13201, doi:10.1029/2012GL052098

New Lunar Lithologies



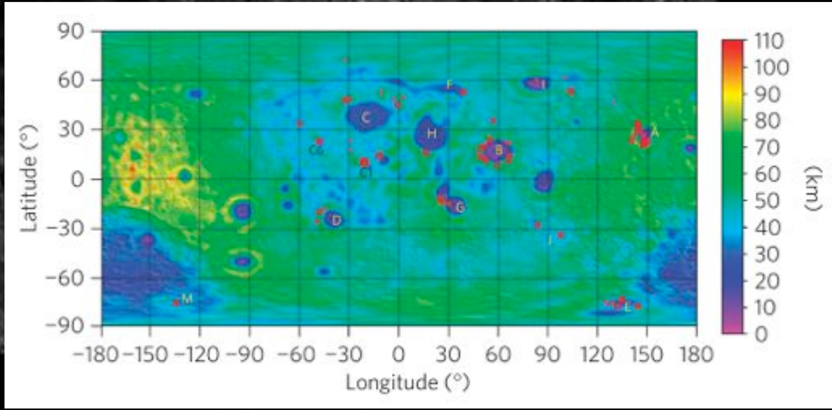
Chandrayaan-1: M3.
Moscoviense Basin

How do these new Rock Types (not represented in the sample collection) revise models of lunar evolution?

Olivine, Orthopyroxene, and Mg-Spinel-rich lithologies ("OOS")

Pieters et al. (2011) *JGR*, **116**, E00G08

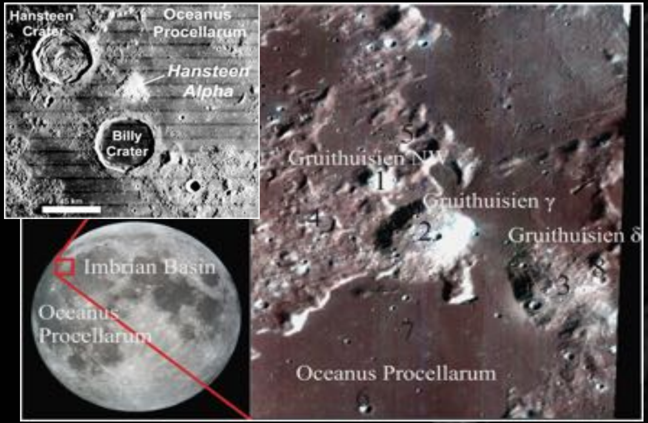
Olivine-rich mantle (?) deposits



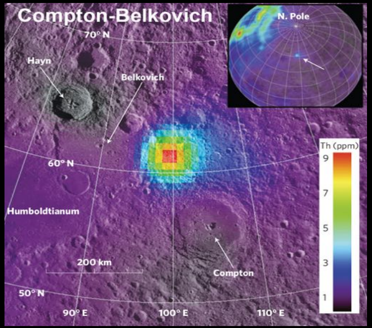
Yamamoto et al. (2010) *Nature Geosci*. **3**, 533-536.

Yamamoto et al. (2012) *Icarus* **218**, 331-344.

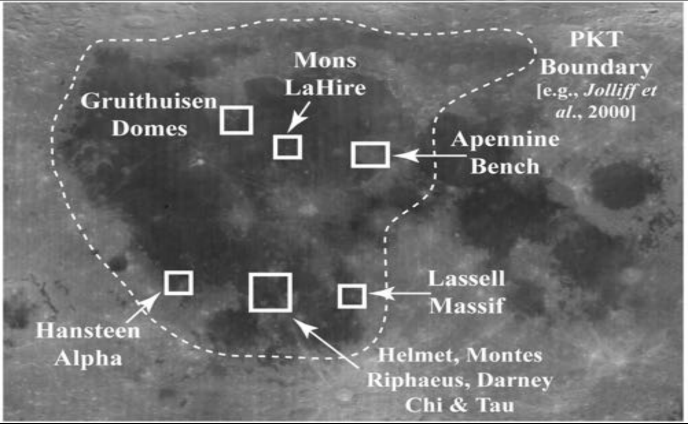
Non-Mare Silicic Magmatism

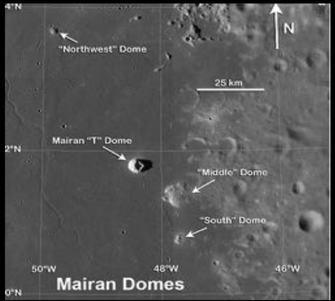


- Enhanced Th;
- Explosive volcanism;
- Christensen frequency (CF) value (DIVINER) indicates silica-rich lithologies.



Can such large Si-rich constructs be formed through SLI?

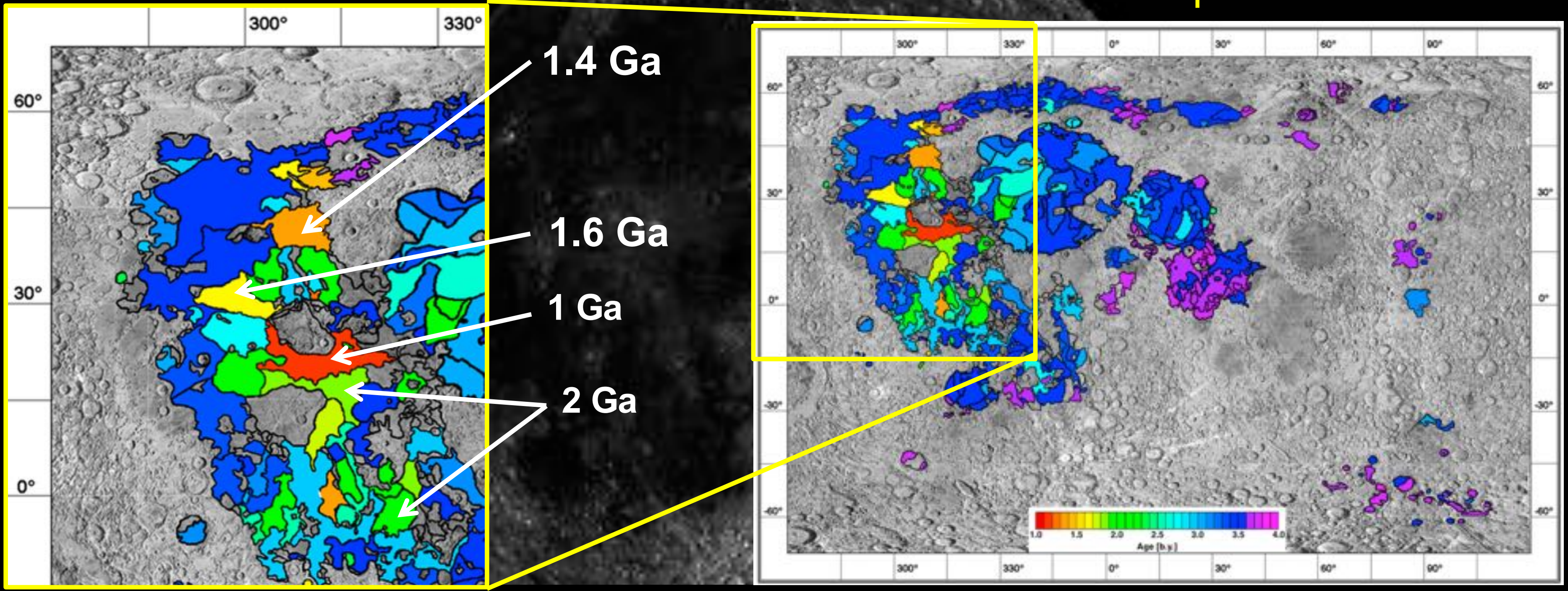




Kusuma et al. (2012) *Planet. Space Sci*. **67**, 46-56.
Jolliff B.L. et al. (2011) *Nature Geosci*. **4**, 566-571.
Glotch T.D. et al. (2011) *GRL* **111**, L21204, doi:10.1029/2011GL049548.
Glotch T.D. et al. (2010) *Science* **329**, 1510-1513
Hagerty et al. (2006) *JGR* **111**, E06002, doi:10.1029/2005JE002592.
Lawrence et al. (2005) *GRL*. **32**, L07201, doi:10.1029/2004GL022022..
Hawke et al. (2003) *JGR* **108** (E7), 5069, doi: 10.1029/2002JE002013.

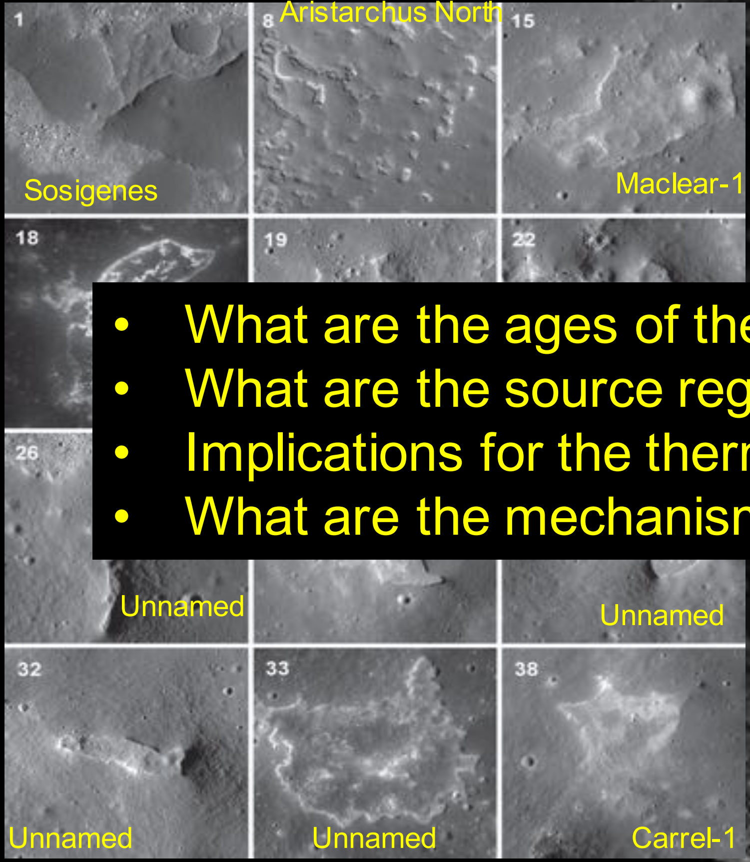
Recent Volcanic Activity

"Recent" volcanic eruptions ~ 1 Ga.



Hiesinger et al. (2003) *JGR* **108**, (doi: 10.1029/2002JE001985)
Hiesinger et al. (2010) *JGR* **115**, E03003, doi:10.1029/2009JE003380
Hiesinger et al. (2011) *GSA Spec. Pap.* **477**, 1-52

Recent Volcanic Activity



Ina depression in Lacus Felicitatis

Schultz et al. (2006) *Nature*, 444, 184-186.

- What are the ages of the IMPs?
- What are the source regions for these potentially ”young” basalts?
- Implications for the thermal history of the Moon?
- What are the mechanisms of eruption?

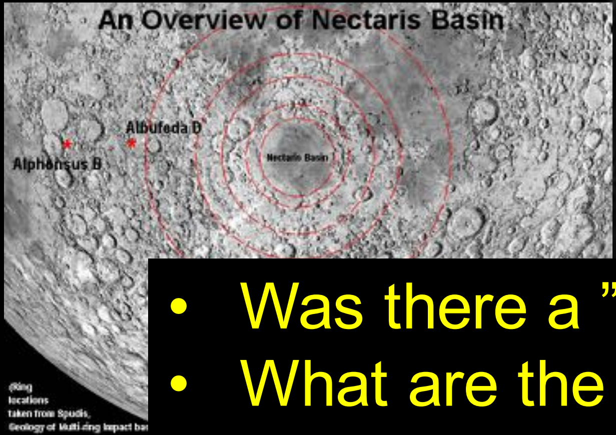
BUT……these are also interpreted to be older (~3.5 Ga):

- Head & Wilson (2017) *Icarus* **183**, 176-223.
- Qiao et al. (2017) *Geology*,

Images = 450 m across

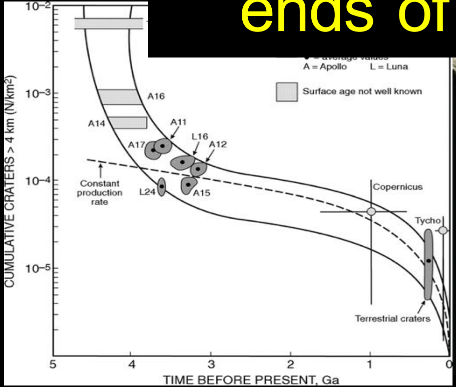
Braden S.E. et al. (2014) *Nature Geoscience*, v. 7, p. 787-791.

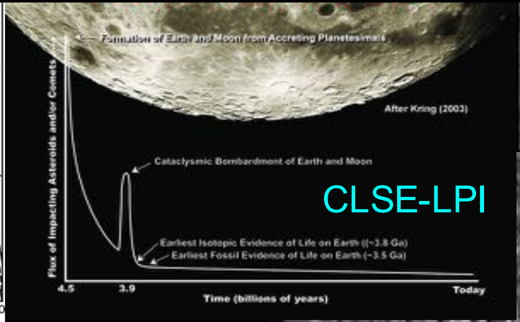
Cratering Chronology



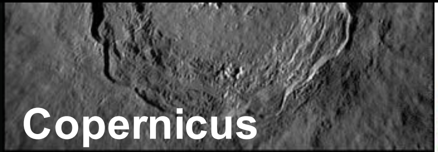
- Constraining crater chronology.
- Important for Solar System Science.
- Need unambiguous impact melt

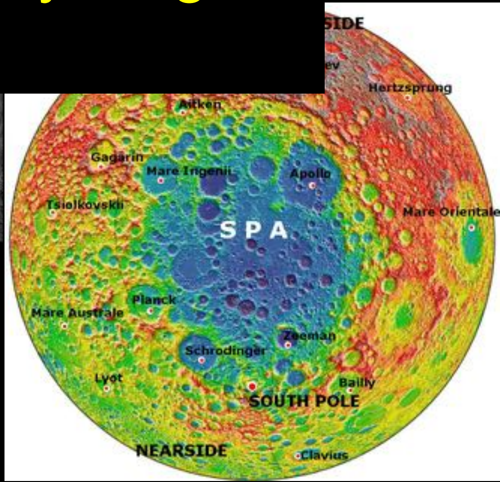
- Was there a "cataclysm" around 3.9 Ga?
- What are the ages/fluxes of the older and younger ends of the crater count curve?





CLSE-LPI

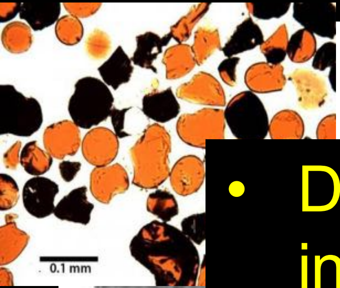


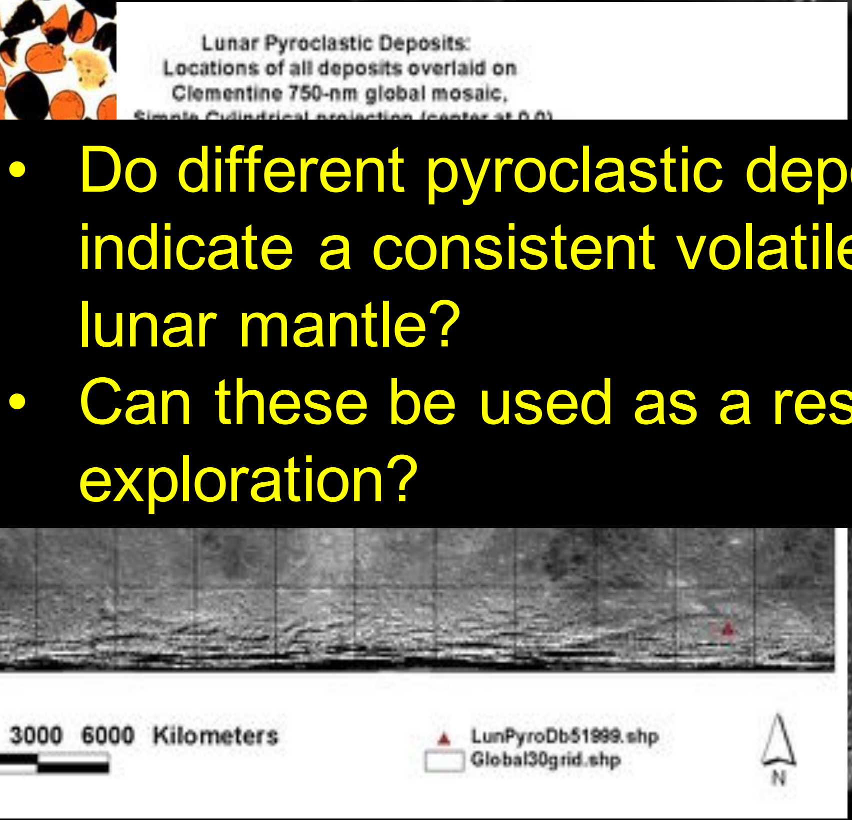


Barlow (2010) *GSA Bull*. **122**, 644-657

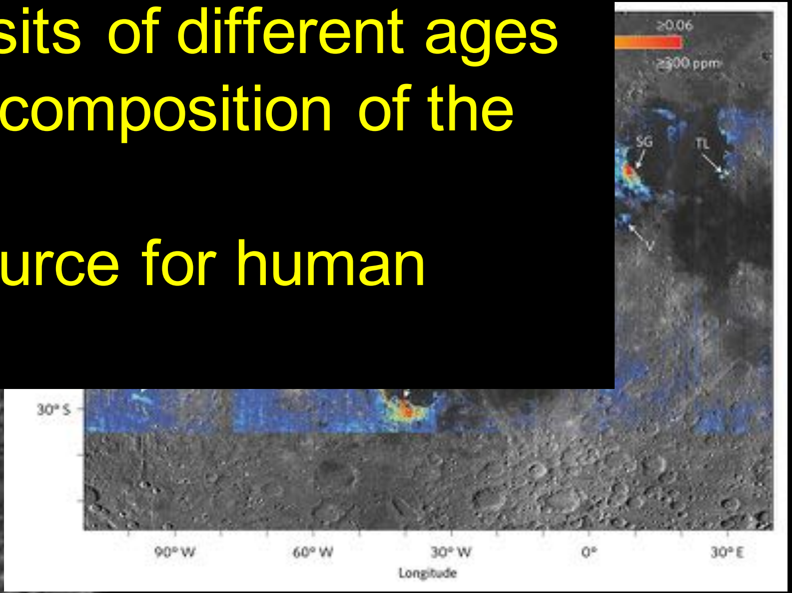
Pyroclastic Deposits

http://astrogeology.usgs.gov/geology/moon-pyroclastic-volcanism-project





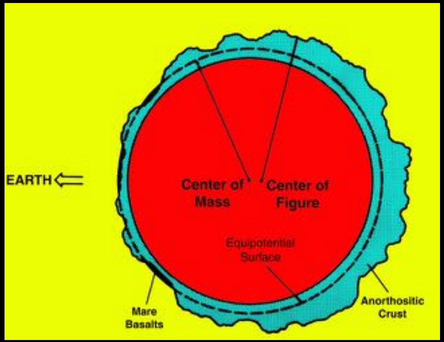
- Do different pyroclastic deposits of different ages indicate a consistent volatile composition of the lunar mantle?
- Can these be used as a resource for human exploration?



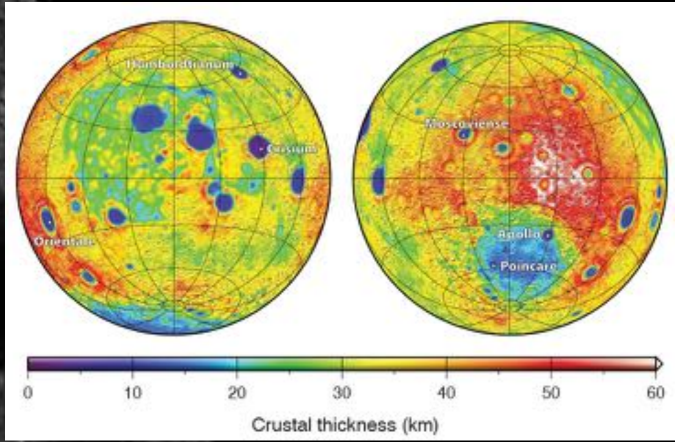
Milliken & Li (2017) Nat. Geosci. 10, 561-565

Farside Highlands

Crustal thickness dichotomy (CoM offset from CoF)



Wieczorek et al. (2013) *Science* **339**, 671-675.



How did the lunar crust form?

Ohtake et al. (2012) *Nature Geoscience* **5**, 384- 388.


LETTERS

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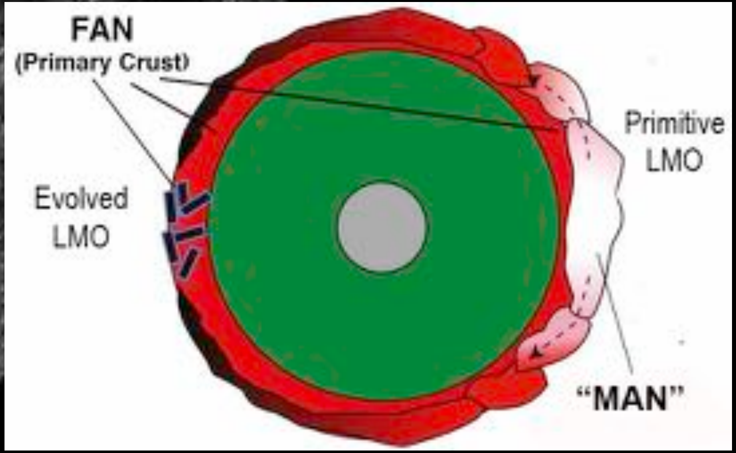
nature geoscience

Asymmetric crustal growth on the Moon indicated by primitive farside highland materials

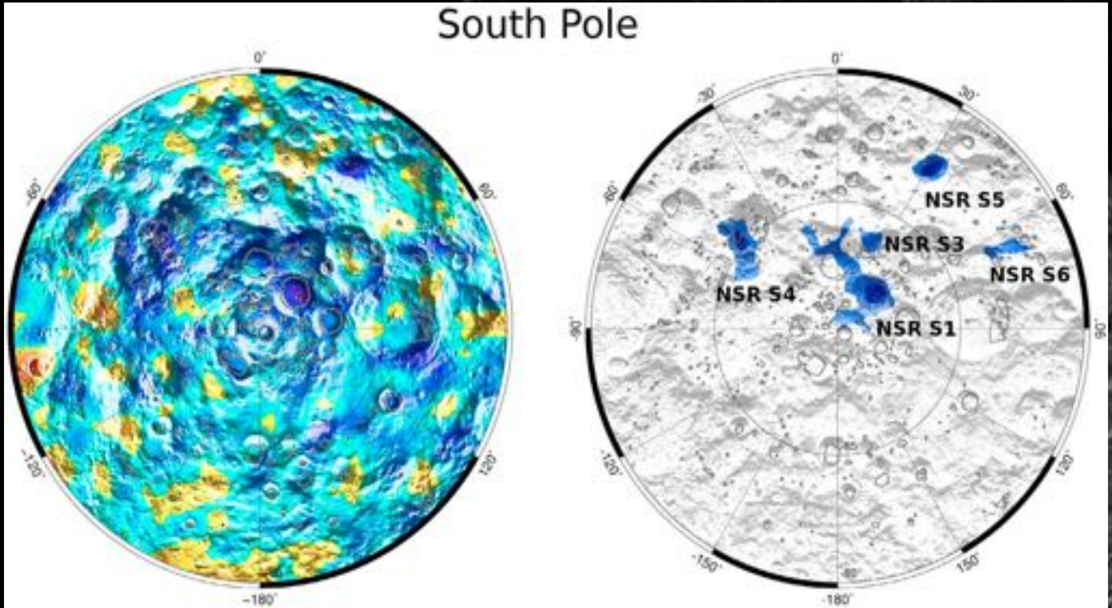
Makiko Ohtake[1]*, Hiroshi Takeda[2], Tsuneo Matsunaga[3], Yasuhiro Yokota[3], Junichi Haruyama[1], Tomokatsu Morota[4], Satoru Yamamoto[3], Yoshiko Ogawa[5], Takahiro Hiroi[6], Yuzuru Karouji[7], Kazuto Saiki[8] and Paul G. Lucey[9]



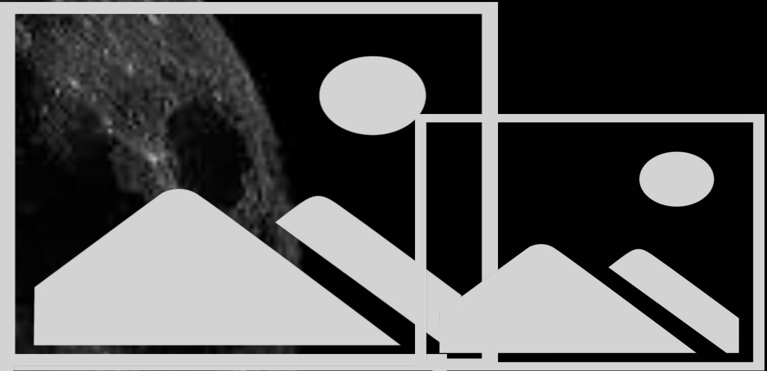
Ice Permafrost Around PSRs

Neutron Suppression Regions (NSRs) are found in both Permanently Shadowed Regions (PSRs) and illuminated areas, and they are not coincident with PSRs.

Possible with nearside sample return?



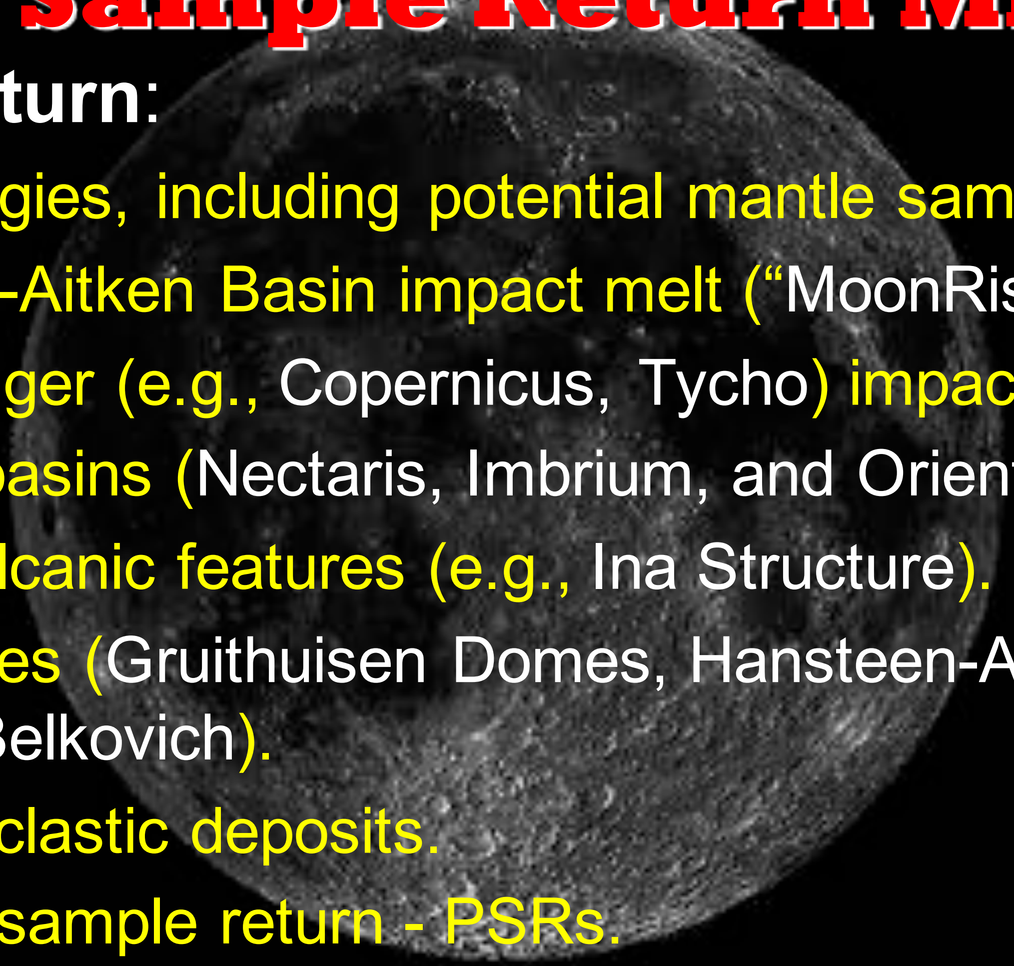
Mitrofanov et al. (2012) *JGR.* **117** E00H27, doi:10.1029/2011JE003956.



LCROSS

Colaprete et al. (2010) *Science* **330**, 463-468.
Colaprete et al. (2012) *Space Sci. Rev.* **167**, 3-22

Future Sample Return Missions



Sample Return:

- New lithologies, including potential mantle samples.
- South Pole-Aitken Basin impact melt (“MoonRise”).
- Other younger (e.g., Copernicus, Tycho) impact craters.
- Multi-ring basins (Nectaris, Imbrium, and Orientale).
- “Young” volcanic features (e.g., Ina Structure).
- Felsic domes (Gruithuisen Domes, Hansteen-Alpha, Compton-Belkovich).
- Large pyroclastic deposits.
- Cryogenic sample return - PSRs.

New Lithologies: Spinel

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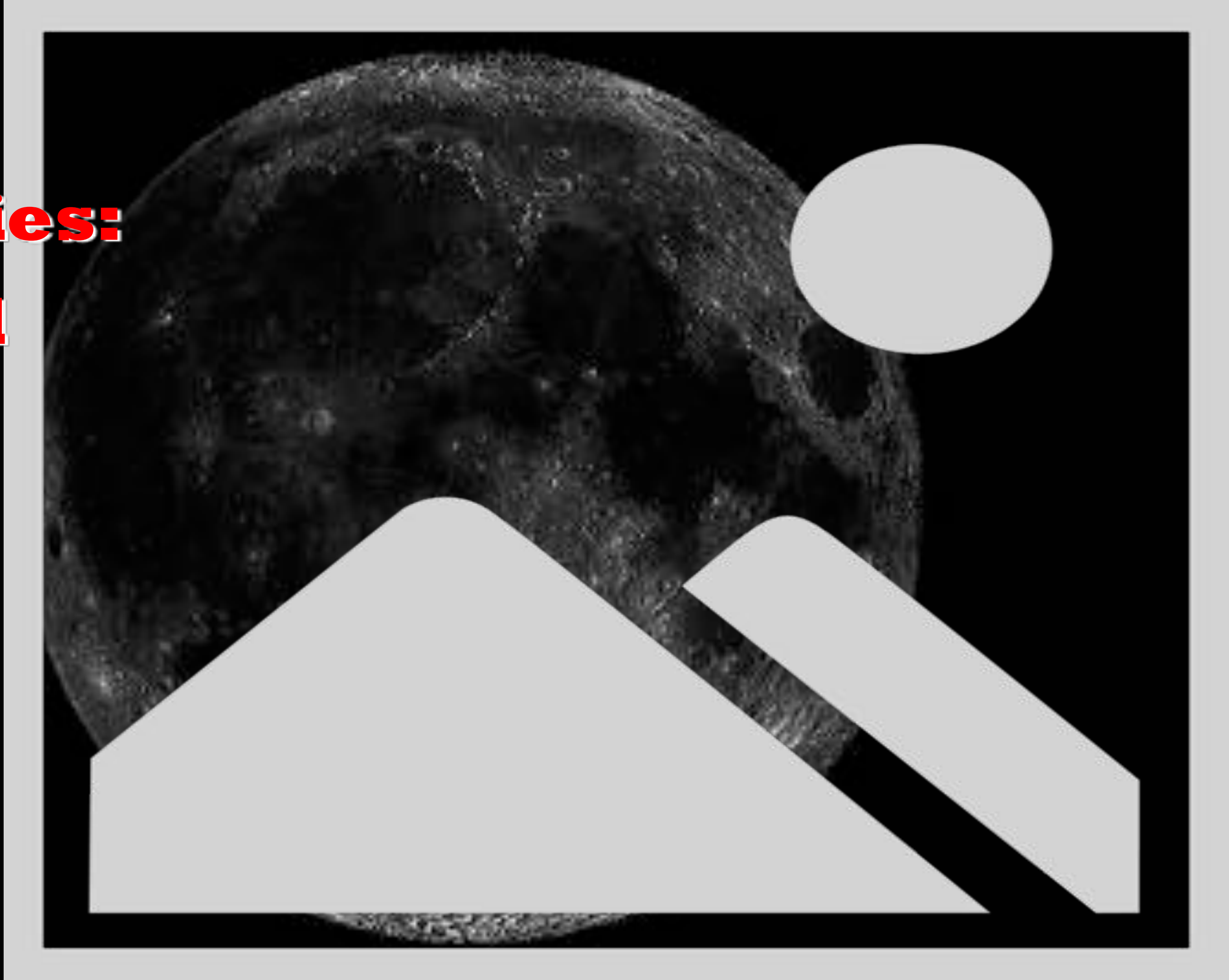

New Lithologies: Mantle?

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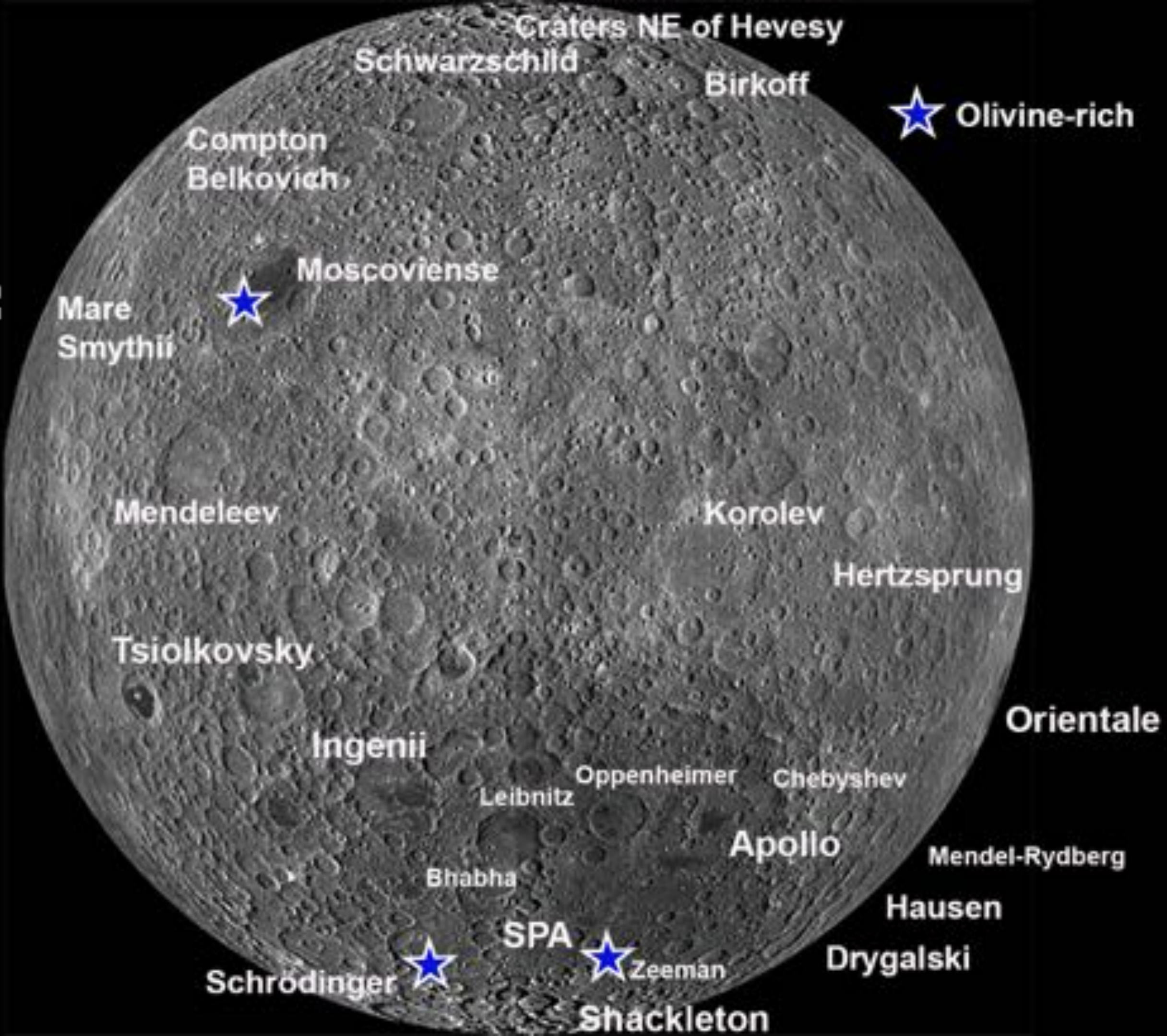
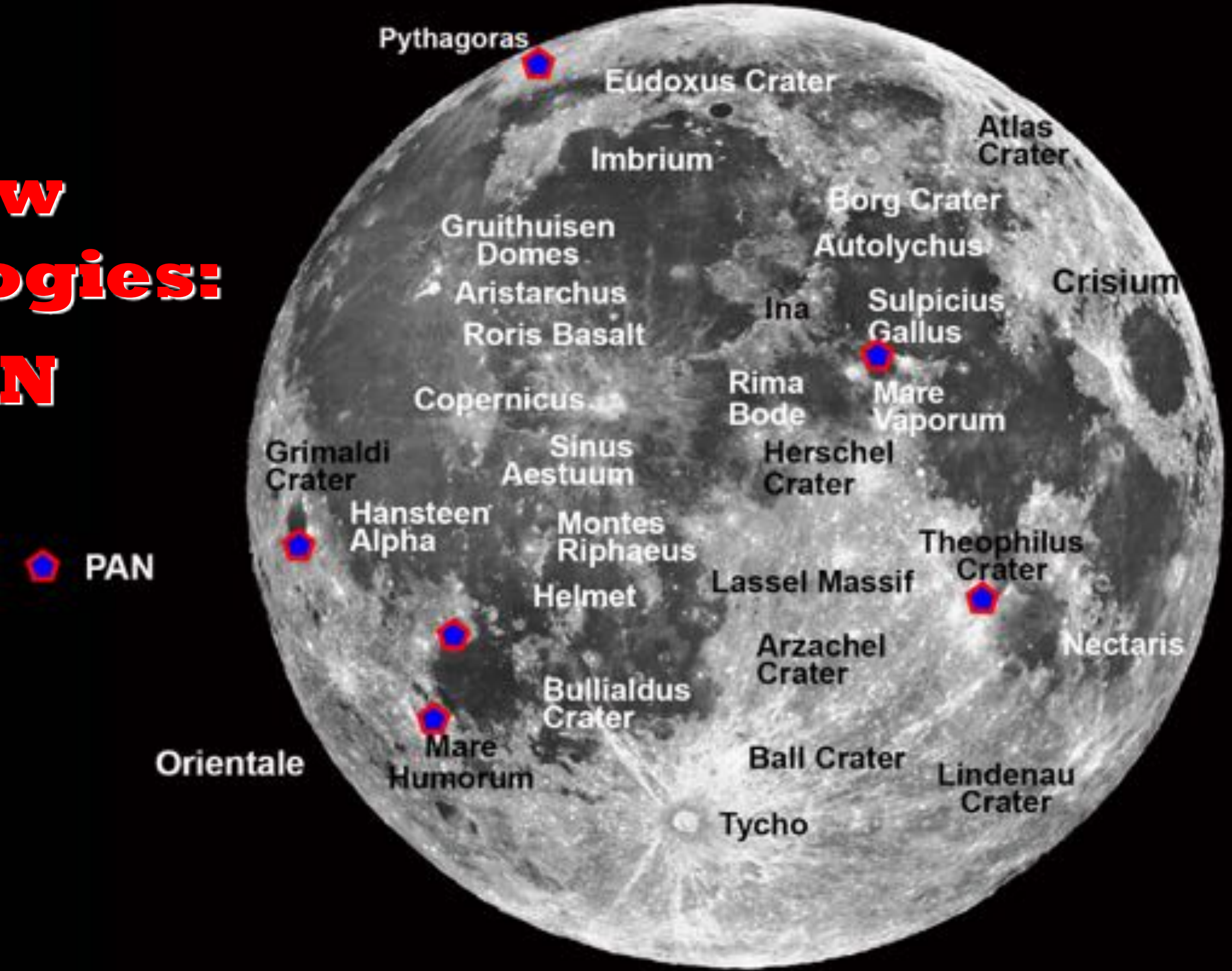
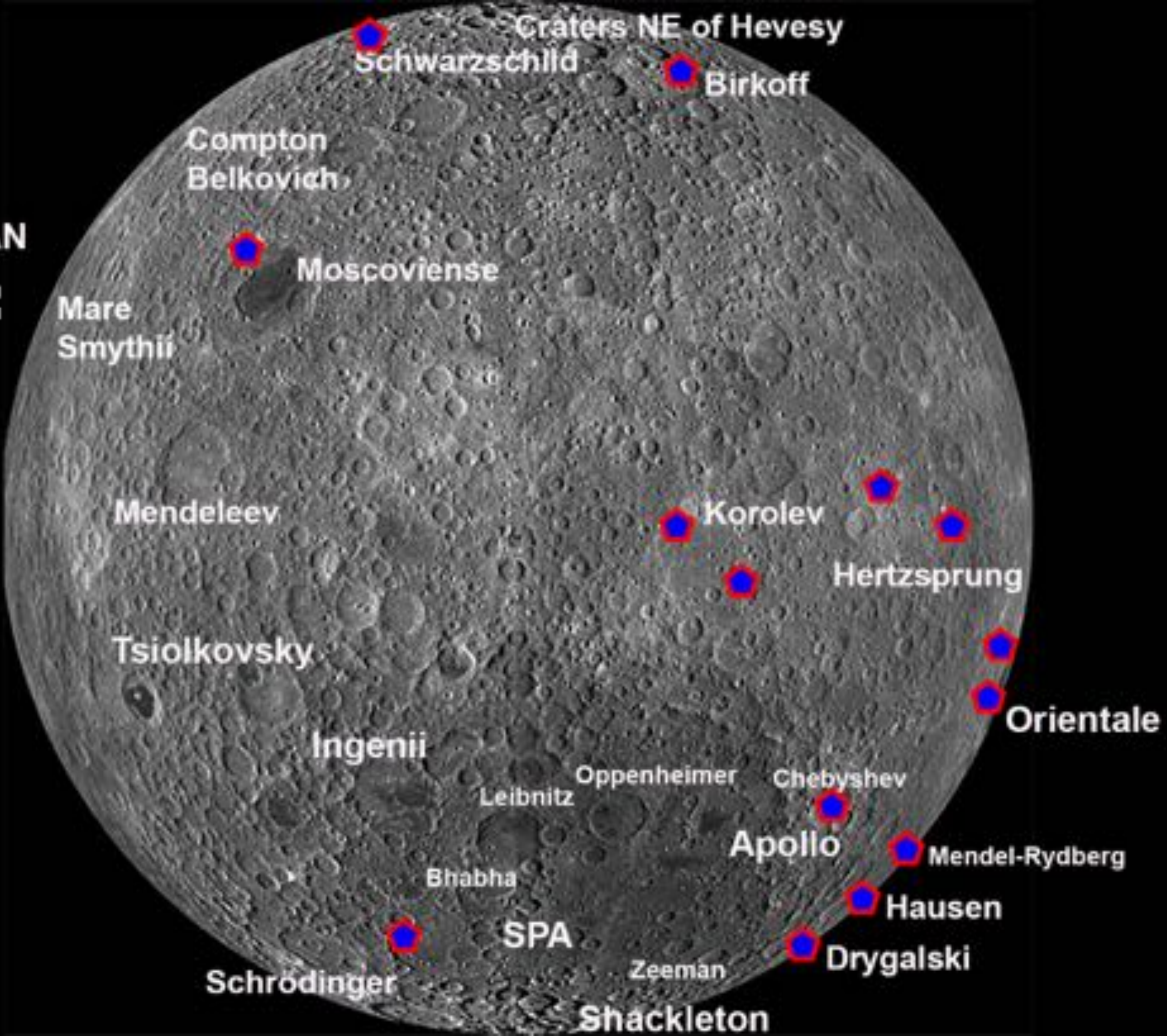


New Lithologies: PAN



New Lithologies: PAN



Felsic Igneous Complexes

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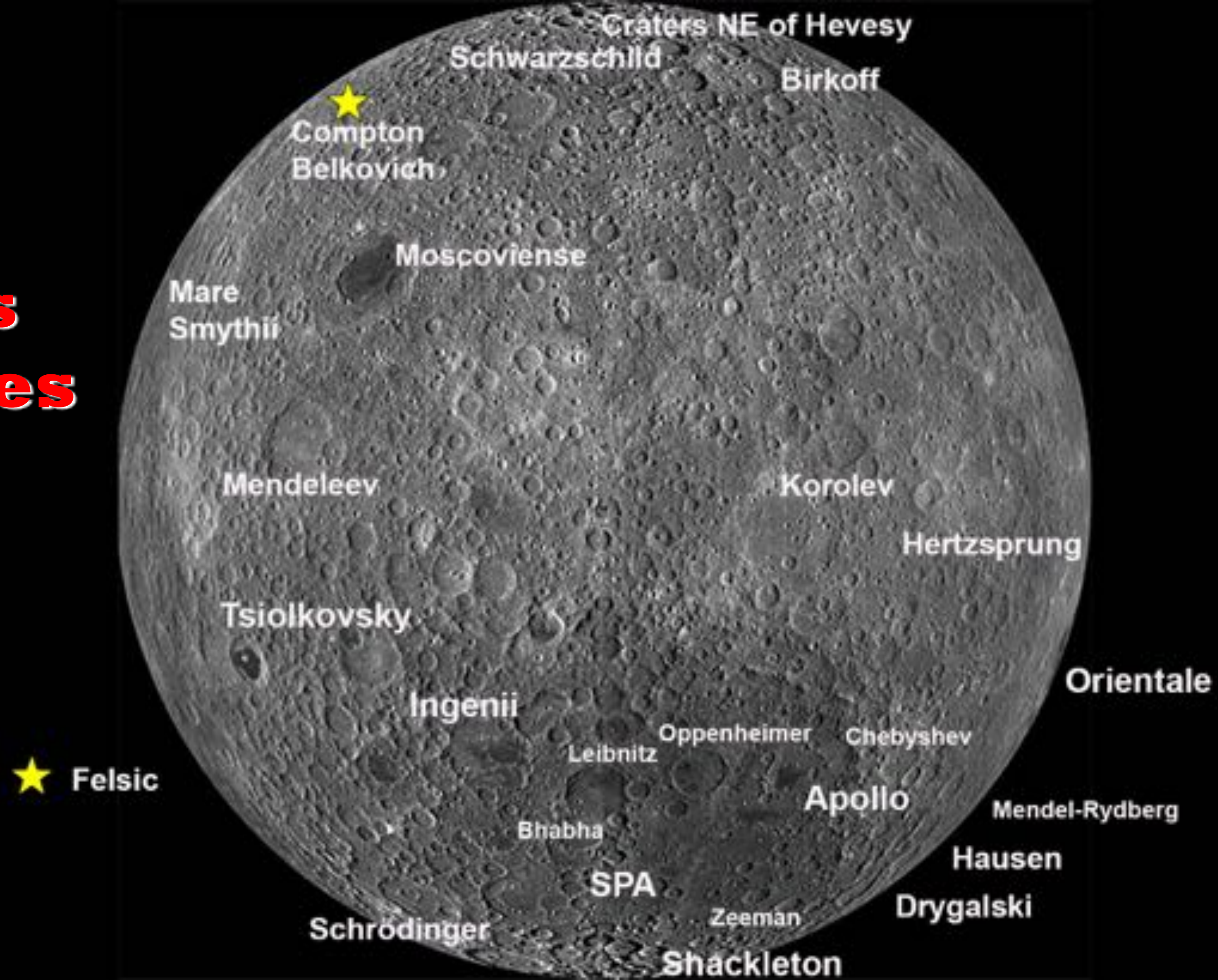
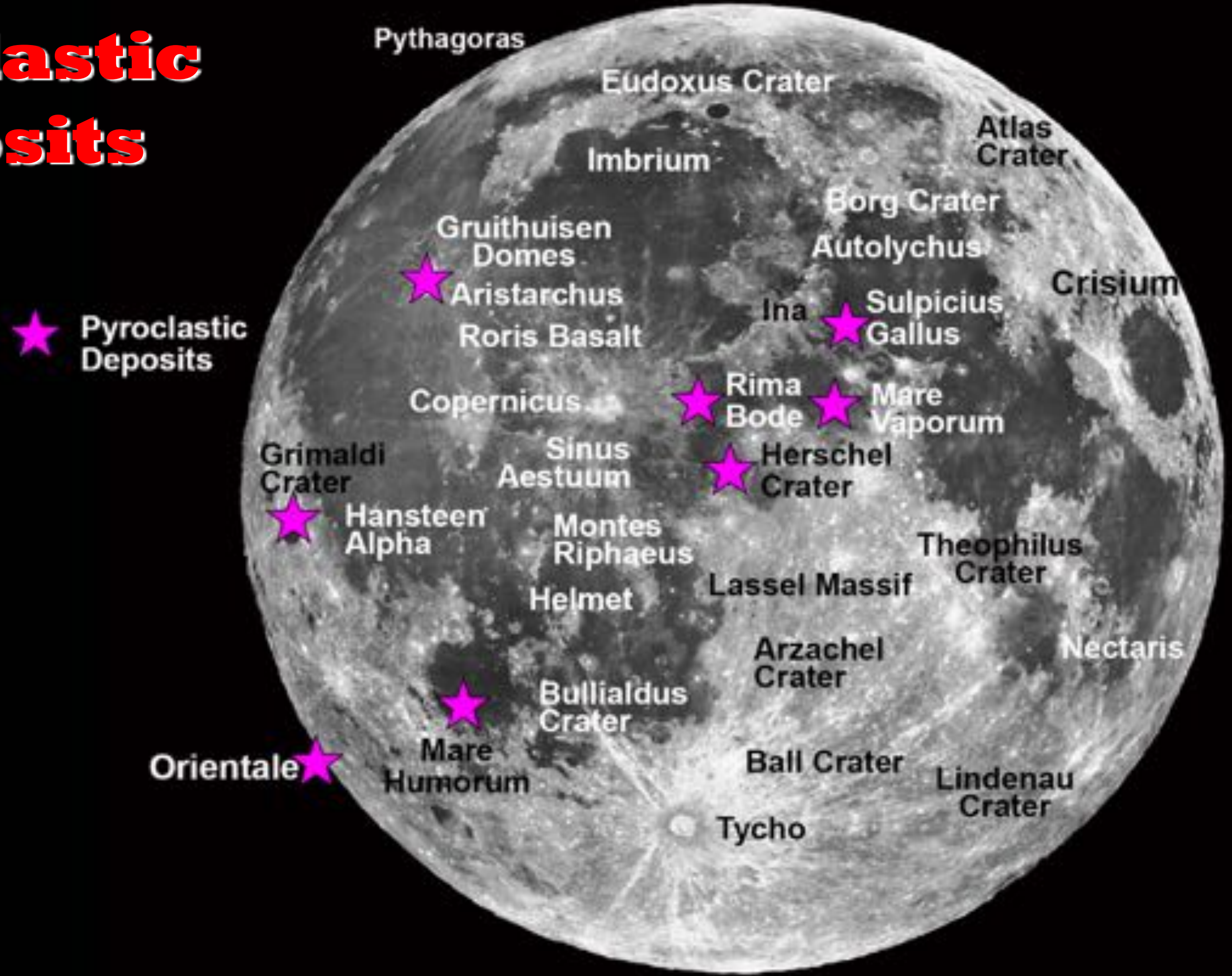
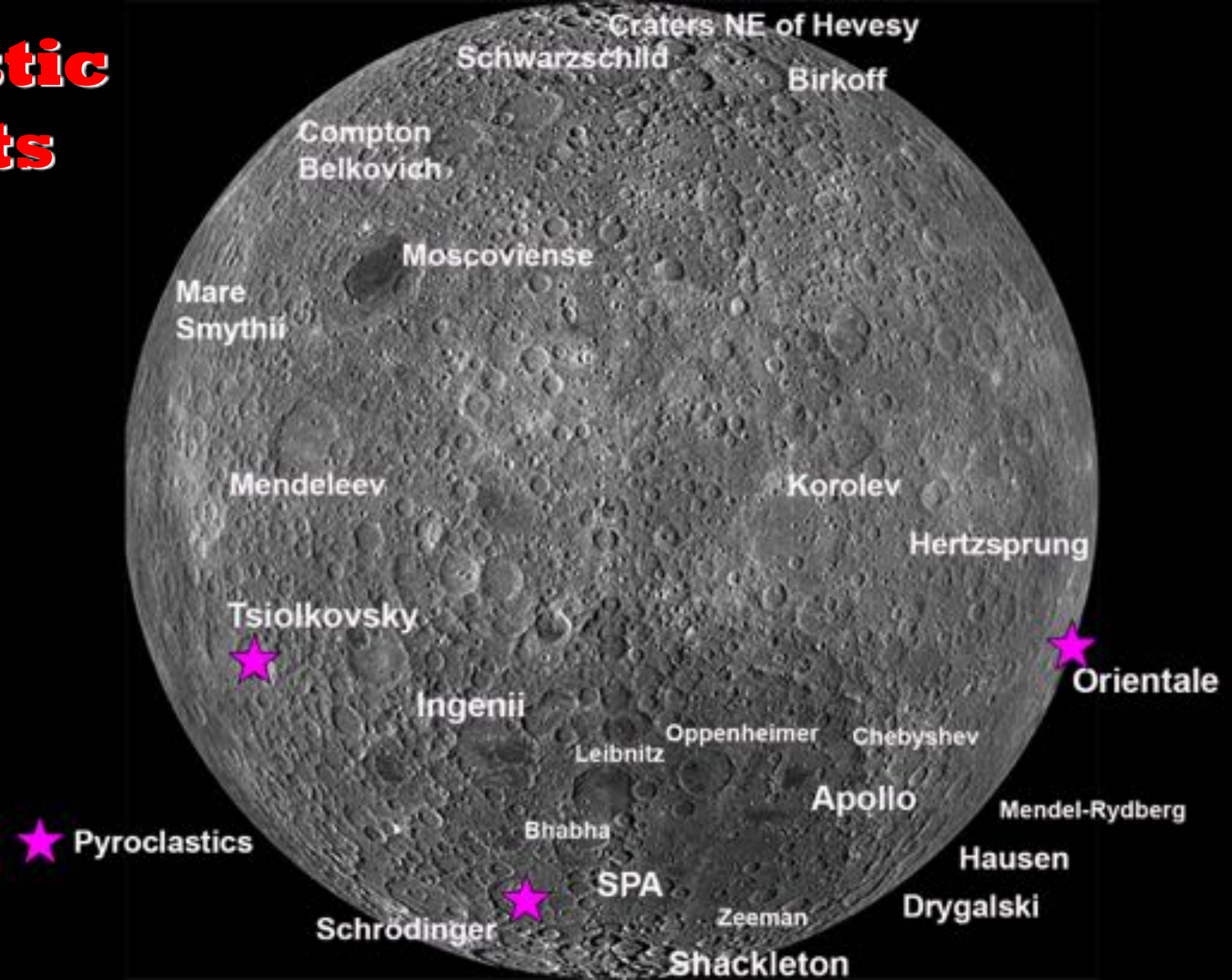


Pyroclastic Deposits



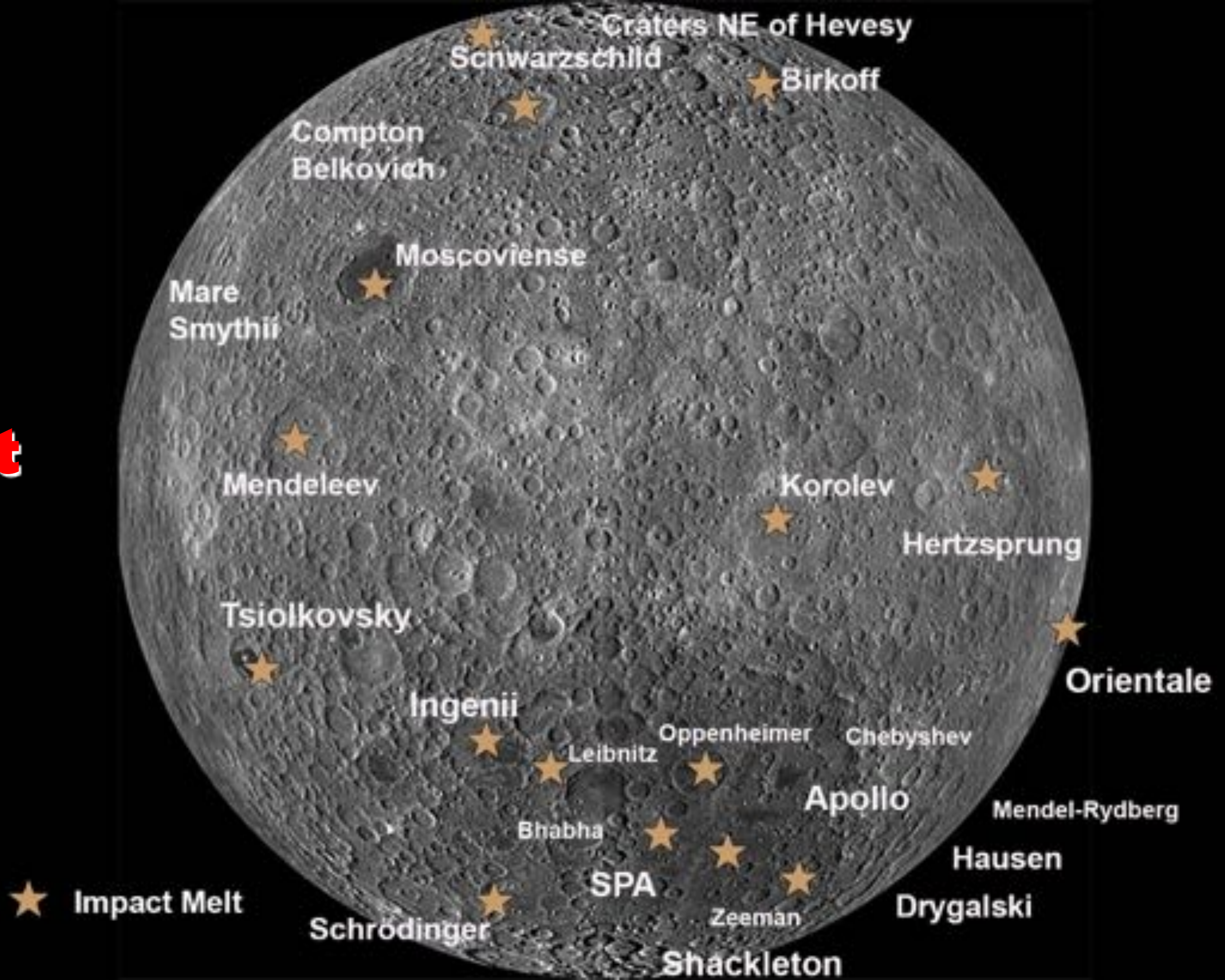
Pyroclastic Deposits



Young Igneous

Impact Melts

Impact Melts



Hydrogen Deposits

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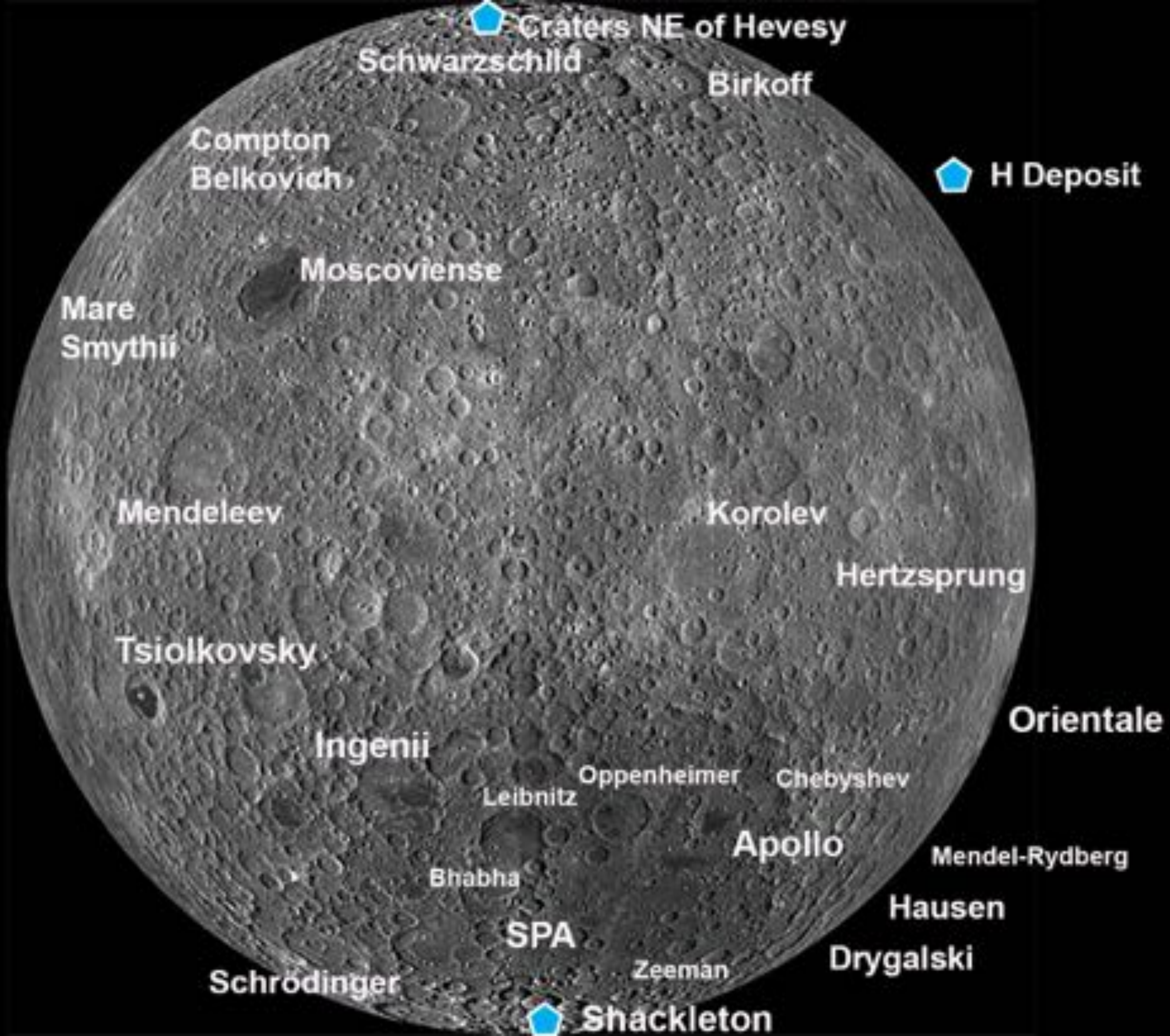
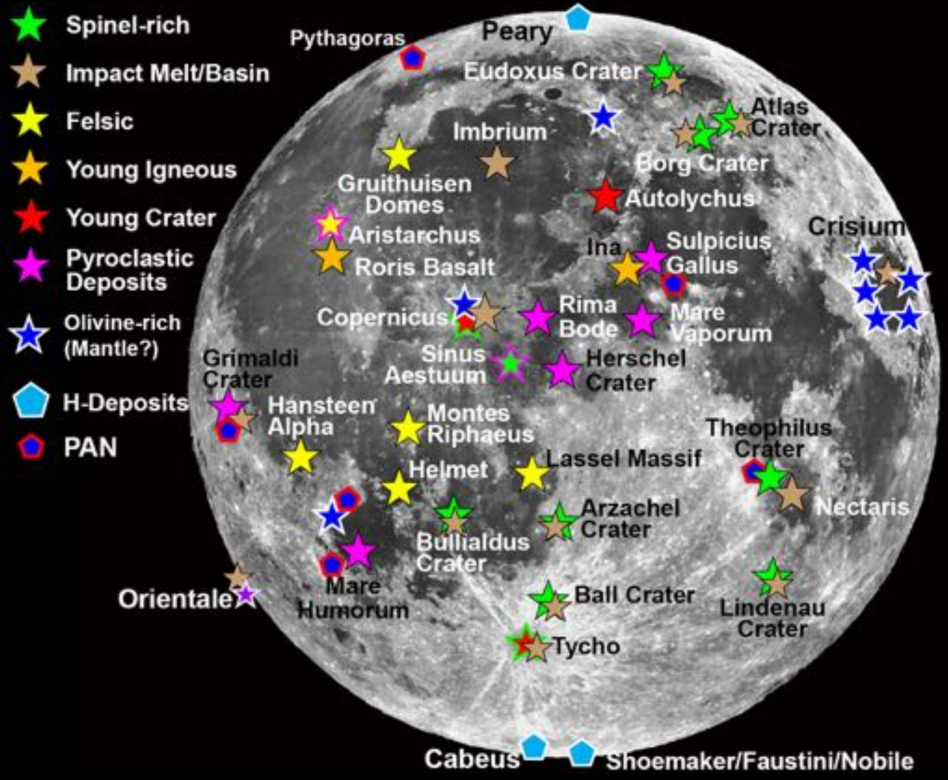
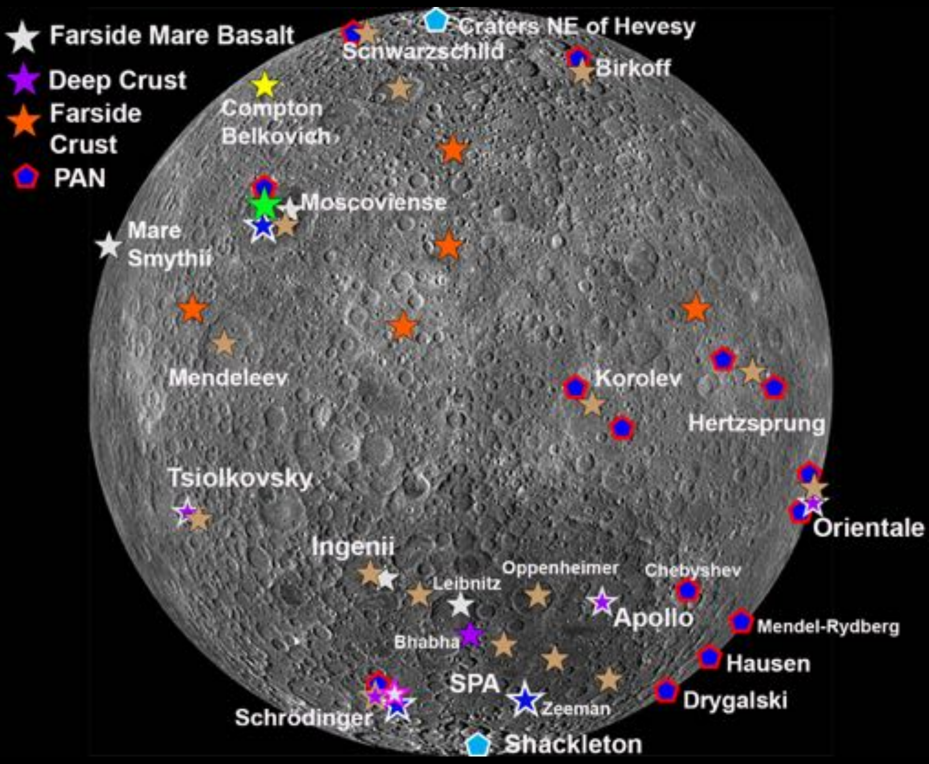


Targeted Sample Return - farside





Technology Development

Robotic SR:

- Landers and sample return vehicles.
- Cryogenic sampling, transport, and curation.
- Rover development to survive the lunar day/night/PSRs temperature swings, sample identification, collection, and storage (including cryogenic capabilities).
- Development of a Moon Assent Vehicle to return the samples.
- These developments would have feed forward implications for Mars sample return or SR from other destinations.

Conclusions

- Private companies are developing lunar surface exploration capabilities, including sample return allowing regular access to Moon.
- Since a regular cadence of missions to the Moon would be required for private commercial companies to build a business case, we have an opportunity to change the paradigm of planetary science and exploration and implement an affordable lunar robotic program.
- A dedicated Lunar Science & Exploration Program (LSEP) Office could be established that involves the lunar community and industrial partners in mission planning and flight opportunities.
- A focused lunar program would allow NASA to be a regular customer while developing new capabilities and implementing at least some of the objectives listed in the Decadal Survey, the LEAG Exploration Roadmap, the SEM Report, etc.